

# Optimization of Deep Borehole Systems for HLW Disposal

---

## Fuel Cycle

Michael Driscoll

Massachusetts Institute of Technology

In collaboration with:

Sandia National Laboratory

JC de la Garza, Federal POC

Robert MacKinnon, Technical POC

## Final Report

# “Optimization of Deep Borehole Systems for HLW Disposal”

September 15, 2015

Award No. NEUP FY 2012 R&D #3298

Contract No. 00126858

MIT Department of Nuclear Science and Engineering

## **FINAL REPORT**

### **September 15, 2015**

**Title:** Optimization of Deep Borehole Systems for HLW Disposal  
**Sponsor:** Battelle Energy Alliance, LLC (BEA)  
**Award Number:** Contract No. 00126858 Nuclear Energy University Program (NEUP)  
**Award Amount:** \$850,000  
**Award Recipient:** Massachusetts Institute of Technology  
**Period of Performance:** 09/01/2012 to 09/01/2015

**Principal Investigator:** Michael J. Driscoll, 617-253-4219 (office), [mickeyd@mit.edu](mailto:mickeyd@mit.edu)  
**Co-Investigator:** E. Baglietto, [emiliob@mit.edu](mailto:emiliob@mit.edu);  
**Other Key Faculty:** J. Buongiorno, [jacopo@mit.edu](mailto:jacopo@mit.edu)  
R. Lester, [rklester@mit.edu](mailto:rklester@mit.edu)  
**Collaborator:** Sandia National Laboratories (SNL)  
P. V. Brady, [pvbrady@sandia.gov](mailto:pvbrady@sandia.gov), 505-844-7146;  
B. W. Arnold, [bwarnol@sandia.gov](mailto:bwarnol@sandia.gov)  
**Technical POC:** Robert MacKinnon, 505-844-1069, [rjmacki@sandia.gov](mailto:rjmacki@sandia.gov)  
**Federal POC:** J. C. de la Garza, 702-295-2334, [JC.DeLaGarza@doe.gov](mailto:JC.DeLaGarza@doe.gov)

#### **Disclaimer**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

## Abstract

This is the final report on a project to update and improve the conceptual design of deep boreholes for high level nuclear waste disposal. The effort was concentrated on application to intact US legacy LWR fuel assemblies, but conducted in a way in which straightforward extension to other waste forms, host rock types and countries was preserved.

The reference fuel design version consists of a vertical borehole drilled into granitic bedrock, with the uppermost kilometer serving as a caprock zone containing a diverse and redundant series of plugs. There follows a one to two kilometer waste canister emplacement zone having a hole diameter of approximately 40-50 cm. Individual holes are spaced 200-300 m apart to form a repository field. The choice of verticality and the use of a graphite based mud as filler between the waste canisters and the borehole wall liner was strongly influenced by the expectation that retrievability would continue to be emphasized in US and worldwide repository regulatory criteria.

An advanced version was scoped out using zinc alloy cast in place to fill void space inside a disposal canister and its encapsulated fuel assembly. This excludes water and greatly improves both crush resistance and thermal conductivity. However the simpler option of using a sand fill was found adequate and is recommended for near-term use.

Thermal-hydraulic modeling of the low permeability and porosity host rock and its small ( $\leq 1\%$ ) saline water content showed that vertical convection induced by the waste's decay heat should not transport nuclides from the emplacement zone up to the biosphere atop the caprock.

First order economic analysis indicated that borehole repositories should be cost-competitive with shallower mined repositories.

It is concluded that proceeding with plans to drill a demonstration borehole to confirm expectations, and to carry out priority experiments, such as retention and replenishment of in-hole water is in order.

## Acknowledgements

The MIT and Sandia collaborators gratefully acknowledge the support provided for this investigation under DOE Award No. NEUP FY 2012 R&D #3298, under BEA Contract No. 00126858.

MIT also acknowledges past support via Sandia, which established the groundwork for this project.

MIT student participants were assisted in their laboratory screening tests by Dr. Thomas McKrell of MIT-NSE and by Prof. Brian Evans and Dr. Ulrich Mok of MIT-EAPS.

Prof. Fergus Gibb and Dr. Karl Travis of Sheffield University continued their useful interactions with the MIT borehole group.

Finally, the MIT Undergraduate Research Opportunities Program (UROP) was generous in support of several of our student participants.

This opus was harmoniously composed, typed and arranged by Richard St. Clair.

## CONTENTS

Section	Page
Abstract	2
Acknowledgements	2
List of Figures	4
List of Tables	4
Chapter 1 Introduction	5
1.1 Foreword	5
1.2 Perspective	5
1.3 Administrative Matters	12
1.4 Organization of This Report	15
1.5 References for Chapter 1	15
Chapter 2 Establishment of a Performance Envelope	16
2.1 Chapter Introduction	16
2.2 Performance Defining Parameters	16
2.3 Chapter Summary	22
2.4 References for Chapter 2	22
Chapter 3 Threats to Excellent Performance	24
3.1 Chapter Introduction	24
3.2 Caprock Plug Leakage	24
3.3 Convective Breakthrough of Water	25
3.4 Loss of Cooling Capability	27
3.5 Other Recent Technically Based Criticism	28
3.6 Chapter Summary	28
3.7 References for Chapter 3	29
Chapter 4 Performance Metrics	30
4.1 Chapter Introduction	30
4.2 Cost of Disposal	30
4.3 Dose to Future Neighbors	31
4.4 Chapter Findings	33
4.5 References for Chapter 4	34
Chapter 5 Summary, Conclusions and Recommendations	35
5.1 Synopsis	35
5.2 Recommendations	37
5.3 Looking Ahead	37
5.4 References for Chapter 5	39
Appendix A: Abstract of PhD Thesis of E. A. Bates	40
Appendix B: Bibliography of Publications for MIT Deep Borehole Projects, 1990 to 2015	41
Appendix C: Draft Transaction Submitted to ANS for Fall 2015 Meeting	45

## List of Figures

Fig. 1.1 Borehole and Plug Design	6
Fig. 1.2 Representative version of deep borehole HLW disposal concept	7
Fig. 1.3. Reference deep borehole canister designs for single PWR and BWR assemblies	8
Fig. 1.4 Announcement: International Meeting on Deep Borehole Disposal of High-Level Radioactive Waste	13
Fig. 2.1 Comparison of vertical Darcy velocity vs. time for the analytical and numerical models, assuming uniform host rock and plug properties in an infinite array of boreholes with 200 meter square spacing	18
Fig. 2.2. PWR Burnup Profiles for Ringhals 3 Reactor Assemblies (960 MWe PWR, 17 x 17 Assemblies)	20
Fig. 3.1. Borehole and Plug Design	25
Fig. 4.1. Optimized lower bound, upper bound and best estimate costs for deep boreholes	31
Fig. 5.1. Model showing Canister End 6-Wheel Roller Ring.	38

## List of Tables

### Table 1.1

Table 1.1 Recommended Configuration of Deep Borehole HLW Repositories	9
Table 4.1 Compilation of Radiological Hazard Rankings for Radionuclides in Granite Mined Repositories	32
Table 5.1 Recommended Configuration of Deep Borehole HLW Repositories	36
Table 5.2 Input to DOE Meeting on Basic Research Needs in July 2015	37

## Chapter 1 Introduction

### 1.1 Foreword

This is the final report for the NEUP FY 2012 R&D 3298 project “Optimization of Deep Borehole Systems for HLW Disposal”

The project objective is best described by the summary paragraph inscribed on the cover of our quarterly reports:

Project objective: The overall goal is to refine and optimize the design of deep boreholes for disposal of nuclear high level waste. The basic configuration is a vertical single-shaft borehole drilled downward (in sequence) through a layer of sedimentary overburden through a layer of high integrity granitic caprock, and then deeper into this basement rock to provide a waste-entombment zone. In addition to characterization and performance assessment of the host rock strata, a major focus will be on post-loading sealing of the borehole in the caprock zone with optimized formulations of materials which provide high-integrity protection against buoyancy-driven upflow via natural convection. The ultimate metrics are long-term dose to a maximally exposed uninformed surface dweller and the cost of waste disposal (e.g. \$/kg HM and/or mills/kWhre) for a prototypic widely useable standard design offering a very high degree of entombment assurance.

As regards bases for assessment, in this project it was implicitly assumed that technical and economic considerations will ultimately determine the future course of action. However, it is widely acknowledged (by present company included) that in the near term sociopolitical factors outweigh virtually all others.

This is not a unique dilemma. For example, the most well-developed and cost-effective renewable option, wind turbines, faces significant siting opposition, even in the Netherlands (Holland), the historical homeland of the windmill (1-1).

At the very least, the case for boreholes should be more widely disseminated, to inform stakeholders and the general public. While not a role for the present project, this aspect has not been ignored. In parallel, for example, MIT and Sandia have published an article in Energy Policy (1-2).

### 1.2 Perspective

An important qualification is that while relevant R&D worldwide is taken into account, the focus in this project was on implementation by the US in the US for disposal of intact US LWR used fuel assemblies having significant post-irradiation cooling. Figures 1.1, 1.2 and 1.3 and Table 1.1 show the principal design features of boreholes as conceptualized for this service.

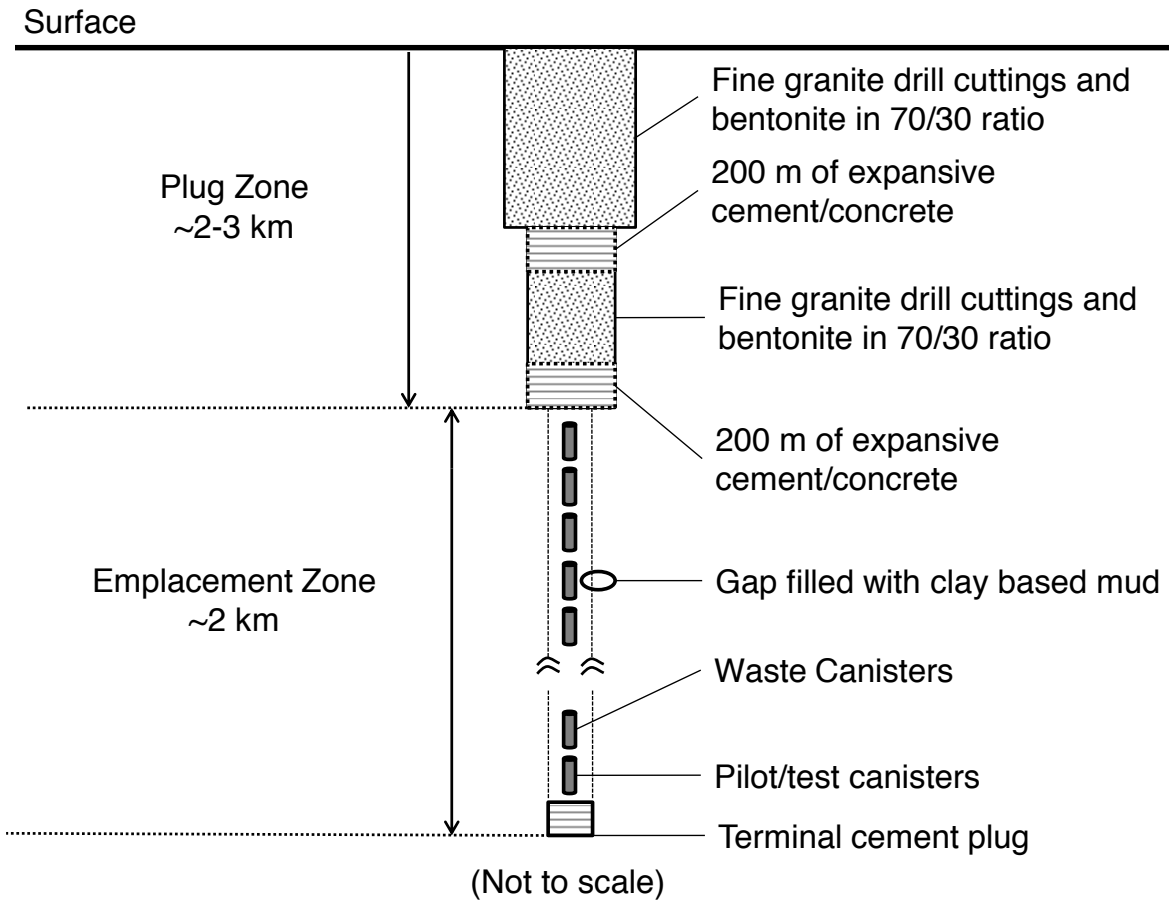


Fig. 1.1. Borehole and Plug Design.

Footnotes:

- (a) plug zone is overburden (if present) atop caprock
- (b) emplacement zone liner is perforated



### **Layout**

Vertical Surface	Hole	Hole	Hole Casing (OD/ID), cm
≤ 1 km Sedimentary rock			} Upper (50.8/48.6)
1 km Basement rock, plug zone			} Mid-Zone (47.3/45.1)
1 km Waste emplacement zone	←→		} Lower (40.6/38.7)
Hole Spacing = 200 m Square Array			

### **Waste String “Canister” Casing**

34 cm OD, 31.5 cm ID\*

5 m length (half of usual 10 m)

Capacity: One PWR Assembly

Weights, kg: Casing\*\* 600

Spent Fuel\*\*\* 700

Sand Fill 700

Total 2000

\*To accommodate 21.4 cm. width PWR assemblies (30.3 cm diag.)

\*\*Including end plugs

\*\*\*Of which 500 kg is (as-loaded) heavy metal

### **Borehole Repository Field**

200 Canisters (assemblies) per hole

100 MTHM/Hole (5 reactor years' worth)

Hole Array: 20 x 40 = 800 Holes, i.e. 4 km x 8 km field

Capacity: 80,000 MT (~Yucca Mountain)

Uranium loading: 100 kg/m as waste,

300 kg/m in rock (@ 3 ppm in granite)

**Cost:**  $4 \times 10^6$  \$ per completed, lined, cemented borehole = 40 \$/kg HM

Fig. 1.2. Representative version of deep borehole HLW disposal concept.

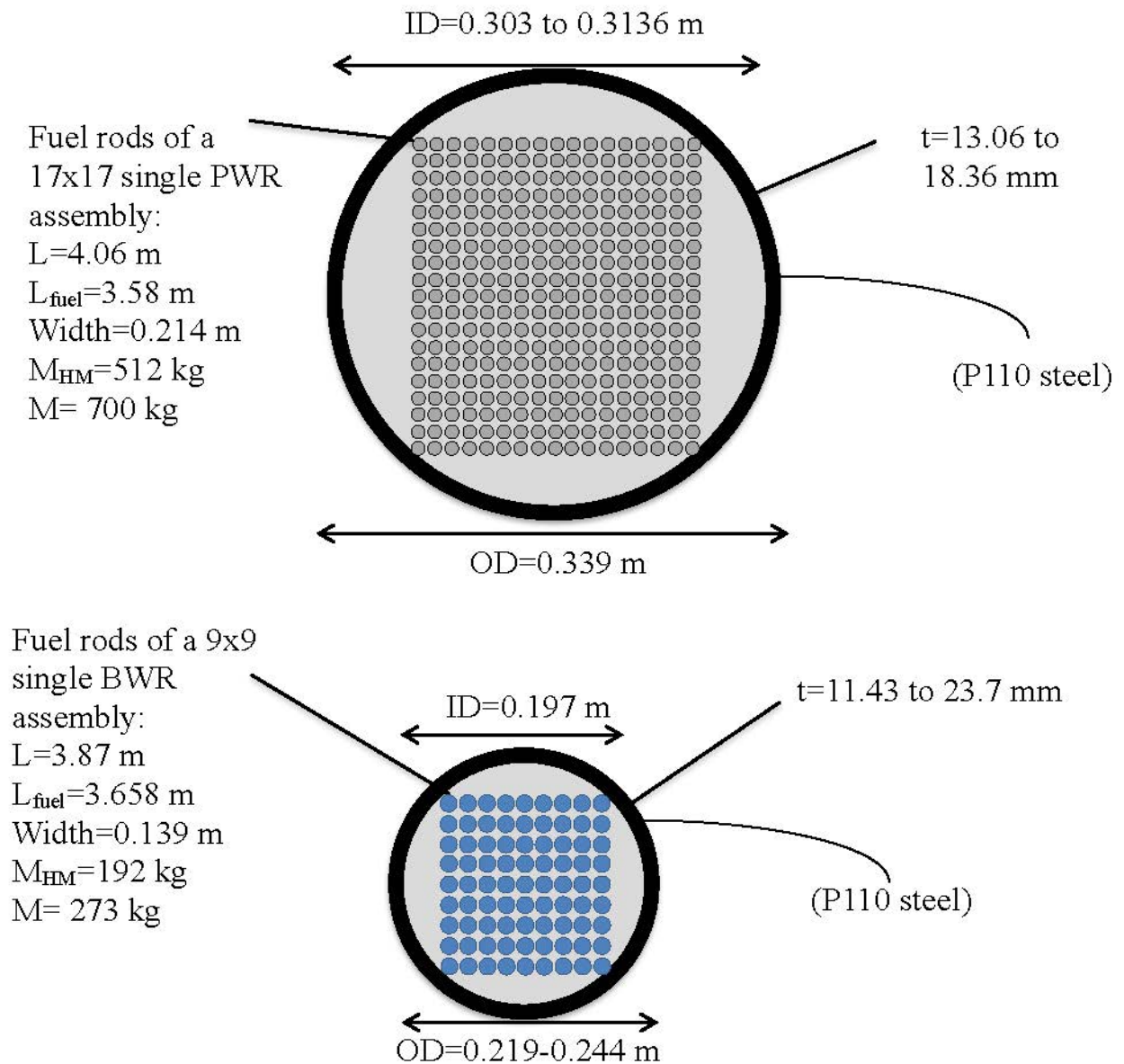


Fig. 1.3. Reference deep borehole canister designs for single PWR and BWR assemblies.

Table 1.1  
Recommended Configuration of Deep Borehole HLW Repositories (as of 9/1/15)

Aspect	Choices*	Motivation
Host medium	granitic bedrock (salt: dome or bedded) [shale or basalt]	dry, with low permeability; ubiquitous availability
Terrain	no sedimentary overburden ( $\leq$ 1km overburden) [shale or salt caprock]	avoidance of increased cost and potential presence of useful aquifers; discourages local habitation
Hole specifications	20 inches: 50 cm ID ~ 1 km of caprock unlined, 1 to 2 km waste zone, lined vertical holes in emplacement zone perforated/slotted liner (slanted holes) [multibranch holes]	<ul style="list-style-type: none"> <li>• to accommodate canisters encapsulating intact PWR fuel assemblies; can reduce for BWR or reprocessing waste forms</li> <li>• to avoid crushing by canister stack</li> <li>• to equalize radial pressure, allow water ingress/egress, gas venting</li> </ul>
Repository field	200 m pitch ~ 400 holes in 20 x 20 array (100m or 300m pitch)	<ul style="list-style-type: none"> <li>• to minimize far future radial temperature peaking</li> <li>• to hold ~80,000 MT (US legacy used fuel)</li> <li>• to realize economies of scale and facilitate collective licensing</li> </ul>
Canister features	made of drillpipe segment (or cast iron cylinder) internal voids filled with granitic sand, (drill cuttings) [or zinc casting alloy] (caster ring on ends)	<ul style="list-style-type: none"> <li>• strong, corrosion resistant under downhole geochemistry</li> <li>• to counter crushing</li> <li>• Zn will exclude water</li> </ul>
Canister/liner gap	fill with graphite/sepiolite mud (other muds), [dry] [concrete with SiC gravel to help thwart retrieval]	high thermal conductivity provides lubrication; blocks vertical convection; facilitates retrieval if this is required. Helps offset stress on hole wall
Caprock plugs	Sequences of: <ul style="list-style-type: none"> <li>• expanding cement</li> <li>• bentonite + granitic sand</li> <li>• [thermite]</li> </ul>	to provide diverse and redundant low permeability seals

\*Near term preferences listed first, alternatives in parentheses ( ); potential future developments in brackets [ ].

In addition to the chapter-by-chapter references identified in support of the work summarized in this final report, a bibliography of some forty-five MIT deep borehole external, (and hence available) reports in the period 1990-2015 is appended. This covers the period before and since the renaissance of MIT work in this area, initially with collaboration and support by Sandia, followed by the 3-year NEUP project summarized herein. Note that the twelve quarterly reports submitted during the NEUP effort are not listed, nor are thirty-four bimonthly progress reports sent by MIT to Sandia under the previous contract. Important results therefrom are covered in the aforementioned external bibliography.

This project deals mainly with the technical aspects of deep boreholes. However, as with all waste disposal considerations, socio-political constraints play an important role. The most noteworthy in the present instance is the issue of retrievability post-emplacement. After considerable internal debate and review of the literature (e.g. Ref. 1-3), it was concluded that future US (and world) regulatory guidelines would probably continue to favor retrievability. One consequence, as will be seen in Chapter 3, is that the gap between waste canisters and the borehole wall liner is filled with graphite mud. Should one instead wish to discourage retrieval – as, for example, boreholes sited in a non-weapons state – the mud could be replaced by a concrete made with silicon carbide gravel. This would greatly complexify recovery in terms of both cost and achievable time spent. Combined with the ability to easily monitor borehole fields using inspectors, satellites or drones, a timely warning would be available to the international community.

Once the backlog of legacy waste has been disposed of – a task which will probably take decades to achieve – another favorable aspect of the borehole concept would come into play. This is the “build as needed, pay as you go” attribute.

The latter characterization of the deep borehole concept also enables incorporation of improvements and innovations in the more distant future.

Among potentially high impact future improvements in technology are:

- ⊙ use of multibranch boreholes: several emplacement holes drilled from a common vertical shaft
- ⊙ an advanced canister design with casters at each end to facilitate use of slant-path boreholes and multibranch boreholes: i.e. roll-in/roll-out capability
- ⊙ improved drilling technology: faster and slightly larger diameter – a synergistic adaptation of projects underway for oil/gas/geothermal applications

An important question left unanswered is whether a borehole loaded with heat generating waste canisters embedded in mud will remain wet, or experience dryout. A related concern is whether a borehole initially loaded dry will, over time, have its void spaces fill with water. These issues can probably only be resolved when a demonstration borehole is drilled into representative granitic host rock and the appropriate experiments carried out. It is important to recognize that heat transfer by

thermal radiation across voided annular gaps (i.e., the dry gap condition) is adequate for legacy waste. In future wastes having higher burnup and shorter cooling times this capability is less certain.

An inherent feature of the deep borehole concept is the dominance of host rock conditions, which supports the presumption that post-waste entombment conditions will eventually return to their verifiably benign pre-borehole conditions. This arises directly from the approximately  $10^4$  to 1 volume ratio of host rock to borehole plus drilling-disturbed zone for a typical borehole field. One can show, for example, that even the small water content of the host rock exceeds borehole void volume by a factor of a thousand, and the uranium content of the host rock equals that in the boreholes even without taking credit for that in the caprock above the waste and bedrock below.

By far, the single most important reference generated during the time covered by this report is the PhD thesis by Ethan A. Bates, “Optimization of Deep Boreholes for Disposal of High-Level Nuclear Waste,” PhD Thesis, MIT Dept. of Nuclear Science and Eng., Feb. 2015. This thesis cites nearly three hundred relevant references in support of its investigations. In view of its major role, the abstract of this thesis is appended to this report.

### Some General Observations

Granitic host rock was selected at the outset in view of its ubiquity as continental bedrock, its favorable geological and geochemical properties, and the vast catalog of information compiled in Sweden and Finland in support of their development and deployment of shallower mined repositories in the Fenno-Scandinavian shield. It should be noted, however, that other strata may also merit attention. In particular salt, both dome and bed type, have long been candidates for HLW disposal in the US. Basaltic bedrock is common underseas. Both shale and salt can serve as very-low-permeability caprock layers atop other rock types. Broadening our scope in this regard is not likely to be needed unless regional socio-political acceptance trumps geology as the dominant consideration.

Our analyses were also restricted to the use of state-of-the-art commercial oil/gas/geothermal well drilling practice. This assures that contracts can be let for delivery of ready-to-use boreholes on a predictable schedule, for an acceptable cost. It should be noted, however, that several research projects are underway in the US to test advanced drilling technologies which are much faster than the rotary bit approach, hence appreciably cheaper. In general, they are based on inducing spallation by localized deposition of highly concentrated beams or fields of energy. Success of any one such approach would greatly enhance prospects for deep borehole waste disposal.

### Policy and Regulation

It would appear plausible that a revision to the 1982 Waste Policy Act, as amended in 1987, will be drafted to revitalize the US repository program in the wake of the trials and tribulations of the Yucca

Mountain Project over the past decade. Preliminary deliberations should be monitored closely to be sure the special attributes of deep boreholes are taken into consideration. Among the more important aspects one should:

- a) remove the prejudice against granitic rock expressed in the 1987 legislation
- b) carefully define what is meant by “retrievability” in the borehole repository context
- c) ratify a two-step licensing process in which a repository field site and specific borehole designs are separately approved (somewhat analogous to that for nuclear reactors)
- d) allow for specialty items which have been proposed for disposal in deep boreholes, such as radionuclide sources (e.g. Sr-90, Cs-137) and nuclear weapons pits.

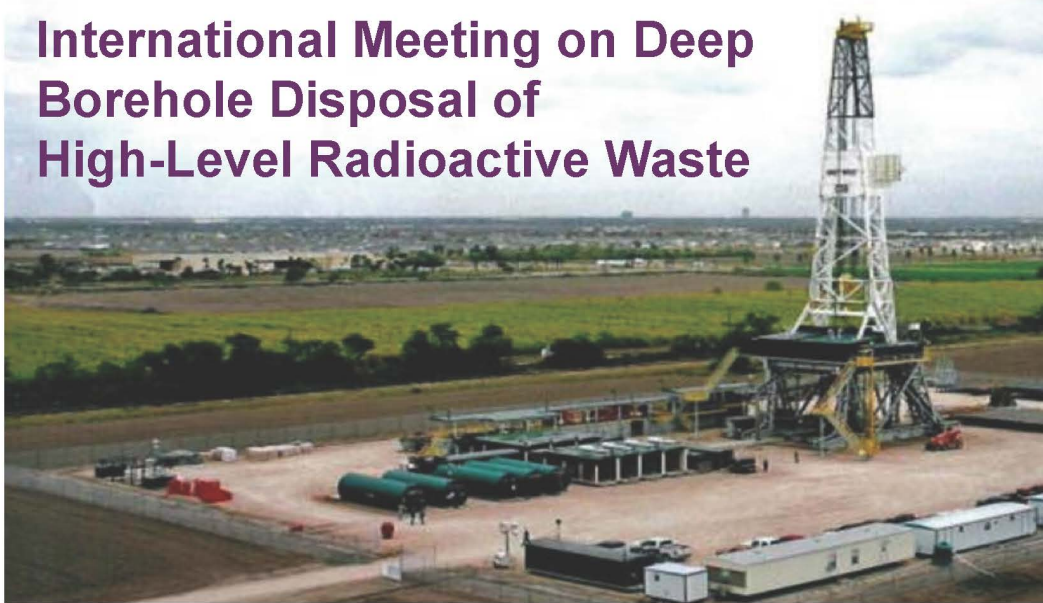
### 1.3 Administrative Matters

#### 1.3.1 Publications and Meetings

An updated bibliography of some four dozen references is appended. It has been expanded to cover all published work on deep boreholes done within the Dept. of Nuclear Science and Engineering at MIT since 1990 (initiation of work under all auspices) through 2015 to date. It does not reference quarterly and annual reports to our sponsors.

Looking ahead, there will be an international meeting on deep borehole disposal of high-level radioactive waste in June 2016 at Sheffield, UK: see attached notice (Fig. 1.4). We will try to see if our MIT group can send a representative. Otherwise someone from Sandia, our official collaborators the past six years, can knowledgeably represent our effort.

## International Meeting on Deep Borehole Disposal of High-Level Radioactive Waste



**13<sup>th</sup> – 15<sup>th</sup> June 2016.**  
**The University of Sheffield, UK.**

An international meeting on the Deep Borehole Disposal of High-Level Radioactive Waste will be hosted by the Deep Borehole Disposal (DBD) Research Group at The University of Sheffield, UK. This meeting comes at a time when significant interest in DBD concepts is being shown by international organisations involved in high-level radioactive waste disposal.

The objective will be to provide a forum for discussions on all aspects of DBD and is aimed at representatives from industry, governmental bodies and policy makers, academic institutions, and non-governmental organisations. The meeting will seek to reach conclusions on concept applicability, and formulate guidelines and recommendations concerning the use of DBD in disposing of specific radioactive waste streams.

The meeting will facilitate discussion of technical, scientific, regulatory and social aspects of DBD, and will consist of keynote presentations, technical items and extensive discussion. These will be based around four main themes:

- Current status of DBD – including technical descriptions of the concepts under development.
- R&D activities and challenges – considerations associated with siting, waste package deployment and recovery, near-field barriers, borehole sealing, and all engineering aspects.
- Foreseeable progression of DBD – details of the likely development of the concept in the medium term.
- Future possibilities and applications of DBD – potential use of the concept at all scales, including centralised and dispersed disposal of a wide range of waste types.

Expressions of interest in further information about the meeting should be sent to the meeting organisers. The preliminary programme and details of registration procedure etc. will be distributed in due course.

### Meeting Organisers

Dr Karl Travis  
Prof. Fergus Gibb  
Dr Nick Collier

### Contact details

Dr Nick Collier, Department of Materials Science & Engineering, The University of Sheffield, Sir Robert Hadfield Building, Mappin St, Sheffield S1 3JD, UK.  
[nick.collier@sheffield.ac.uk](mailto:nick.collier@sheffield.ac.uk)

Fig. 1.4 Announcement: International Meeting on Deep Borehole Disposal of High-Level Radioactive Waste

### 1.3.2 Student Participants

Over the three-year course of this contract the following students have been involved at a significant level of effort:

Rodríguez Buño, Mariana (Ph.D. candidate, Civil Engineering) moved to our TerraPower TWR contract as of last Fall

Park, Yongsoo (graduate student research assistant) will remain through end of this contract, then move to TerraPower project for Fall 2015

Lubchenko, Nazar (SM student) has completed and submitted his SM thesis and has moved to another unrelated contract. Internship at EDF, Summer 2015

Andriatis, Alex (undergraduate) has completed his UROP project and departed for a summer internship off campus

Everett, Patrick (undergraduate) has completed his UROP project and departed for a summer internship off campus

Formento Cavaier, Roberto (visiting grad. student) has completed his SM thesis and submitted it to Politecnico di Torino.

Wium, Elsmari: Completed a UROP project and submitted a report in 2013

Diaconeasa, Mihai: Graduate Research Assistant during part of 2013

Salazar, Alex– SB thesis student, MIT Dept. of Nuclear Science & Eng., May 2013, currently graduate student at UC Berkeley

De Maio, William – undergraduate student, MIT Dept. of Nuclear Science & Eng, Class of 2016

Bates, Ethan – PhD student, thesis submitted Jan. 2015, currently at TerraPower



## 1.4 Organization of This Report

The enumerated chapters which follow cover the following topics from a retrospective point of view – i.e. based on 20-20 hindsight:

Chapter 2 documents how an overall final parameter space was determined based on the realization that the only plausible mechanism for radionuclide escape to the biosphere is by waterborne transport, as driven by thermal-expansion of water in the granitic host rock.

Chapter 3 examines the role of thermal-convection-driven flow as a potential major augmentor of upward transport. Most importantly, a quantitative case for its lack of efficacy is made.

Chapter 4 This brief synopsis summarizes the current best estimates by project staff of the ultimate performance metrics of cost per kilogram spent fuel, and potential radiation exposure to the reasonably maximally exposed individual.

Chapter 5 concludes, with a summary of findings and recommendations.

Appendices:

Abstract of PhD Thesis by Ethan Allen Bates

Bibliography

## 1.5 References for Chapter 1

(1-1) “Dutch Quixote: Why the Dutch Oppose Windmills,” The Economist, Vol. 416, No.8945, July 4, 2015

(1-2) E. A. Bates, M. J. Driscoll, R. K. Lester, B. W. Arnold, “Can Deep Boreholes Solve America’s Nuclear Waste Problem?” Energy Policy, Vol. 72, Sept. 2014

(1-3) Nuclear Waste Governance: An International Comparison, A. Brunnengröber & 4 others (eds.), plus 23 contributors. Springer VS (2015)

## Chapter 2 Establishment of a Performance Envelope

### 2.1 Chapter Introduction

In retrospect, the most useful outcome of this evaluation is arguably the analysis which led to the definition of parameters and their interdependencies which define a space within which deep boreholes can reliably sequester radioactive wastes (e.g. used LWR fuel assemblies).

While complex computer code simulations played an important role in this regard, they proved to be most valuable in the validation of simple “back-of-the-envelope” models which provide conservative analytic expressions for characterizing performance metrics.

In this chapter several such are derived and exercised:

- ⊙ upflow water velocity driven by thermal expansion
- ⊙ time for host rock water content to penetrate the caprock which separates the waste-bearing zone from the surface biosphere
- ⊙ peak post-entombment temperatures inside the waste canisters and in the surrounding host rock
- ⊙ the efficacy of failsafe features such as radiation heat transfer under hypothetical post-dryout scenarios

Each of the above are discussed in the section which follows.

### 2.2 Performance Defining Parameters

#### 2.2.1 Vertical Escape Velocity

Although our initial focus was on water-borne natural convection as the potentially dominant way for radionuclides to escape confinement, it was soon discovered that thermal expansion of the water contained in the host rock was more important and of more certain occurrence. It is also particularly simple to model.

Consider a 200 m x 200 m cell of host rock surrounding a borehole in an infinite array. Assume the very small volume fraction of water in the rock (~1%) is at the same temperature as the rock.

Then one has:

$$\text{Cell volume} = 8 \times 10^7 \text{ m}^3$$

Cell heat capacity for a specific heat of 0.79 kJ/kg°C and a rock density of 2750 kg/m<sup>3</sup>:

$$\text{MCp} = 1.74 \times 10^{11} \text{ kWs/}^\circ\text{C} = 0.55 \times 10^4 \text{ kWyr/}^\circ\text{C}$$

Then if all decay energy goes into host rock heatup, a thermal power balance gives:

$$P = q'h = MCp \frac{d(\Delta T)}{dt}$$

where  $q' =$  linear decay heat power  $\approx \frac{2.2 \text{ kW} / \text{m}}{t^{3/4}}$

and  $t =$  years since end of power operation

$h =$  length of emplacement zone = 2000 m for this test case

The fractional increase in water volume per unit time is given by

$$\frac{1}{V} \frac{dV}{dt} = \bar{\alpha} \frac{d(\Delta T)}{dt} = \bar{\alpha} \frac{2.2 h}{MCp} t^{-3/4}$$

in which  $\bar{\alpha} =$  thermal expansion coefficient for water (average over range of interest) – e.g.,  $\sim 6 \times 10^{-4}$  per °C between 50°C and 100°C

Finally, assume the increase in water volume appears as an increase in vertical height inside its capillary flow tubes and cracks, in which case its fractional increase in height per unit time is just:

$$\frac{1}{V} \frac{dV}{dt} = \frac{1}{h} \frac{dh}{dt} = \frac{1}{h} \hat{v} \quad (8)$$

where  $\hat{v}$  is the rate of upflow (i.e. escape or penetration velocity).

Combining results:

$$\hat{v} = \frac{2.2 \alpha h^2}{MCp} t^{-3/4}, \text{ m / yr} = \frac{2.2(6 \times 10^{-4})(4 \times 10^6)}{(0.55 \times 10^4)} t^{-3/4} \quad (9)$$

$$\hat{v} = 96 \times 10^{-2} t^{-3/4} \text{ m / yr}$$

$$\approx 10^{-3} t^{-3/4} \text{ km / yr}$$

and when  $t = 10^4$  years

$$\hat{v} = 10^{-6} \text{ km / yr}$$

The above value is the vertical rise velocity in the small cracks or capillaries containing the water: i.e. the “escape” velocity.

We assume water-filled porosity,  $\phi$  is the same fraction of capillary volume and cross-sectional area.

Thus superficial (or Darcy) velocity is just  $v_s = \phi \hat{v}$ , and for  $\phi = 0.01$ , as in the present example

$v_s = 10^{-8} \text{ km / yr}$  at  $t = 10^4$  yrs ( $3.2 \times 10^{-13} \text{ m/s}$ ); and the extrapolated value at 1 yr is therefore  $10^{-5} \text{ km/yr}$ .

This is in good agreement with calculations made using our thermal-hydraulic code: see Fig. 2.1. It follows that the time to traverse the caprock zone is also consistent, despite the simplicity of this approach.

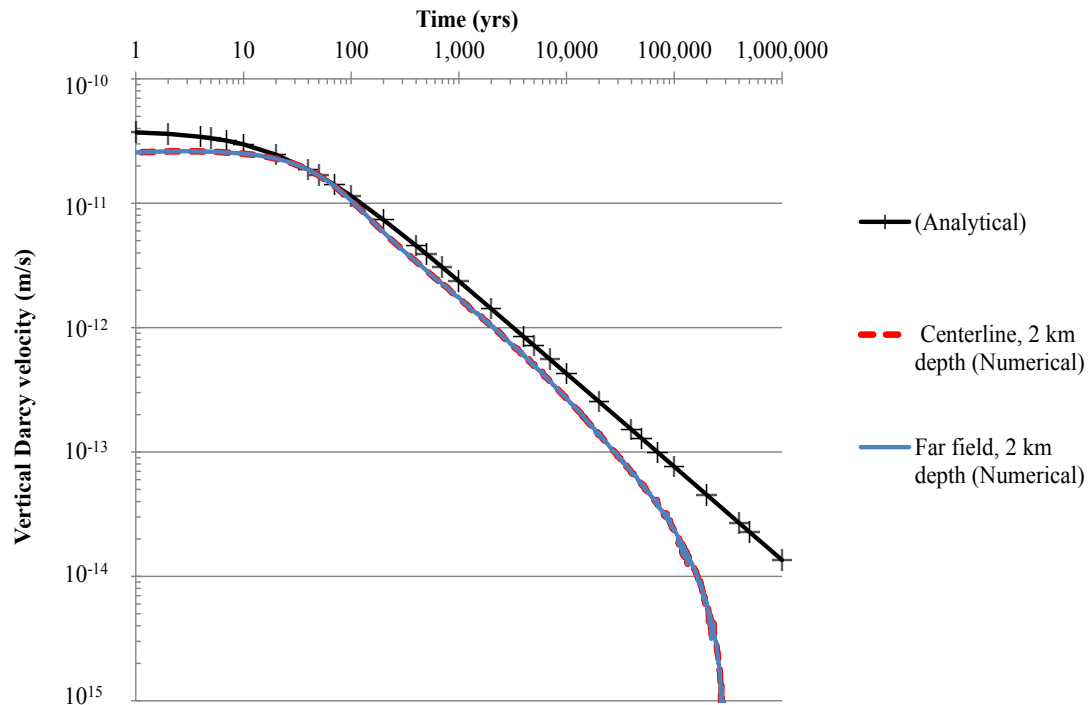


Fig. 2.1 Comparison of vertical Darcy velocity vs. time for the analytical and numerical models, assuming uniform host rock and plug properties in an infinite array of boreholes with 200 meter square spacing. (From Ref 2.3)

### 2.2.2 Caprock Transit Time

Results using coupled thermal-hydraulics codes show that water rise velocity in the caprock zone becomes proportional to the decay heat rate of the entombed waste after an initial transient period of about 100 years.

Hence we can write for the escape velocity, for LWR spent fuel:

$$v_e(t) = \frac{\hat{v}(1)}{\phi} t^{-\frac{3}{4}}, \text{ km/yr} \quad (1)$$

where  $\hat{v}(1)$  = superficial (i.e. Darcy) velocity, km/yr

at a (back-extrapolated) time of 1 year

$\phi$  = host rock interconnected porosity

Thus the time to rise the thickness of the caprock, H km, (i.e. escape) is given by the relation:

$$H = \int_0^{t_e} v_e(t) dt, \text{ km} \quad (2)$$

Solving:

$$t_e \cong \left( \frac{\phi H}{4\hat{v}(1)} \right)^4, \text{ years} \quad (3)$$

Then, for example, let H = 1 km, and

$\hat{v}(1) = 10^{-5} \text{ km/yr} \cong 10 \text{ mm/yr}$ , and

$\phi = 0.01$ ,

in which case

$t_e = 3.9 \times 10^9$  years, essentially forever, even compared to the half-life of I-129 at 15.7 million years.

The modeling effort at MIT prior to 2015 has employed an approximate correlation for LWR used fuel decay heat as a function of cooling time based on the study reported by Xu (2-1), based on his extensive parametric computations using the ORIGEN2 code of 1980 vintage. This motivated a time to the -3/4 approximation.

A recent re-examination using a decay history provided by Sandia researchers (as documented in our Ref (2-2)) suggests that the -3/5 power may be a better descriptor.

The single most affected consequential analysis is the time it takes for the thermal expansion of water to propel penetration of the caprock overlying the borehole host rock. As noted above, -3/4 yielded an estimate proportional to caprock thickness to the 4<sup>th</sup> power. The new slope of -3/5 reduces this dependence to the 2.5 power and  $t_e$  is then  $3.2 \times 10^6$  years – much less sensitive but still impressive. At present no changes in the reference design borehole field appear justified, in view of the extreme overconservatism throughout.

However, future work should be done using an actual time history for calculated decay heat rather than the overly simplistic log-log envelope we have employed so far.

### 2.2.3 Peak Post-Entombment Temperatures

The temperature endured during inaccessible entombment is of obvious interest for any and all waste disposal schemes. Deep boreholes have an advantage in this respect because of the large surface area to volume ratio of single assemblies compared to the larger assembly bundles characteristic of most mine-type repositories.

Fortunately, fairly accurate estimates can be made using simple analytic models. As shown in Fig. 2.2, the burnup, hence decay power, profile is fairly uniform, which allows use of a one-dimensional (radial) line source model.

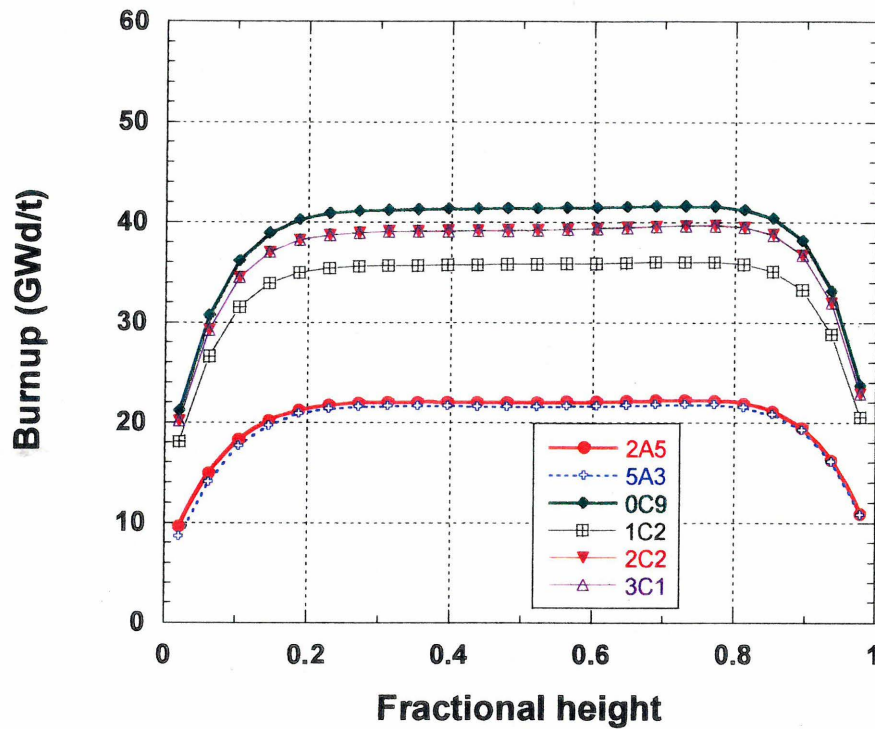


Fig. 2.2. PWR Burnup Profiles for Ringhals 3 Reactor Assemblies (960 MWe PWR, 17 x 17 Assemblies), from Ref (2-4)

Inside the borehole this supports use of the well-known relation for central-to-surface temperature difference in a homogenized cylinder:

$$\Delta T = \left( \frac{q'}{4\pi k} \right)$$

Thus if  $q' = 100 \text{ W/m}^2$  for a 40-year-old discharged assembly of PWR legacy fuel, and if the effective homogenized thermal conductivity is conservatively taken to be  $0.4 \text{ W/m}^2$  (roughly that of dry sand), then  $\Delta T = 20^\circ\text{C}$ , which is tolerable initially, and decreases with time.

The rock temperature assessment is more complicated since it increases to a maximum over a period of several years as the heating propagates radially early-on. The transient peak  $\hat{\Delta T}$  between the hole surface and far afield can be shown, by numerical integration of the one-dimensional time-dependent model, and input of granitic host rock parameters, to be well-approximated by (2-5):

$$\hat{\Delta T}; 7 \left( \frac{q'}{4\pi k_r} \right)$$

where  $k_r$  is now rock thermal conductivity ( $\sim 2.5 \text{ W/m}^\circ\text{C}$ ), in which case  $\hat{\Delta T} = 22^\circ\text{C}$ , hence of no real concern.

#### 2.2.4 Radiation Heat Transfer across Gaps

Linearization of the radiation heat transfer relation across a narrow planar gap gives for the effective thermal conductivity:

$$k_r \cong \frac{4\sigma \delta \bar{T}^3}{\left[ \frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1 \right]} \left( 1 + \underbrace{\frac{1}{4} \left[ \frac{\Delta T_g}{\bar{T}} \right]^2}_{\ll 1, \text{ neglect}} \right), \text{ W/mK}$$

where  $\sigma$  = Stefan-Boltzmann constant =  $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$

$\delta$  = width of gap, m

$\bar{T}$  = average of surface temperature, degrees K

$\epsilon_1, \epsilon_2$  = emissivity of surfaces 1 and 2

$\Delta T_g = T_1 - T_2$  = temperature drop across gap

and, for a thin annulus of diameter  $d$ :

$$\Delta T_g = \frac{q'' \delta}{k_r} = \frac{q' \delta}{\pi k_r d}$$

where  $q''$  = heat flux,  $\text{W/m}^2$

$q'$  = linear power,  $\text{W/m}$

For example, let

$$\bar{T} = 400^\circ\text{K} = 127^\circ\text{C}$$

$$\delta = 0.02 \text{ m}$$

$$\epsilon_1 = \epsilon_2 = 0.8$$

$$d = 0.32 \text{ m}$$

take  $q' = 100 \text{ W/m}$ , for a PWR legacy fuel assembly

then  $q'' = q'/\pi d = 99.5 \approx 100 \text{ W/m}^2$

Then  $k_r = 0.194 \approx 0.2 \text{ W/m}^\circ\text{C}$

and  $\Delta T_g \approx 10^\circ\text{C}$ , a quite tolerable value.

It follows that dryout downhole is not an important impediment, even if several gaps in series are involved. Also note that a complete dryout which included the host rock would exclude water-borne radionuclide transport!

Demonstration borehole confirmation of this prediction using an electrically heated waste canister simulator should be part of any future deep borehole RD&D program.

If instead  $\epsilon \approx 0.9$ , as for blacker (e.g. graphite coated) surfaces  $\Delta T_g$  is only 20% lower; but for polished metal having  $\epsilon = 0.2$ ,  $\Delta T_g$  is higher by a factor of six. This could be problematic for used fuel having much higher decay power. Thus, consideration should be given to blackening of exposed surfaces – as currently practiced for solar power towers, for example.

### 2.3 Chapter Summary

This chapter looks back at how the iterative design process has converged upon a set of parameters which act in concert to define attributes of a successful deep borehole repository configuration.

Our focus has been on the small amount of water normally present in granitic basement host rock, since this is the only plausible carrier of radionuclides up into the occupied biosphere. It was shown that heatup of the rock by radionuclide decay, and thus that of its contained water, defines an escape time and required caprock thickness.

Also demonstrated was that a two hundred or so meter spacing between boreholes in a repository field can limit self-induced downhole heatup to tolerable levels for LWR legacy waste.

Finally, even if complete dryout were to take place due to some not as yet identified mechanism, it was shown that falling back on reliance upon the totally passive mechanism of radiation heat transfer sets a tolerable limit on overheating.

### 2.4 References for Chapter 2

(2-1) Z. Xu, M.J. Driscoll, M.S. Kazimi, “Design Strategies for Optimizing High Burnup Fuel in Pressurized Water Reactors,” MIT-NFC-TR-053, July 2003

(2-2) N. Lubchenko, “Transient Modeling of Host Rock for a Deep Borehole Nuclear Waste Repository,” SM Thesis, MIT Dept. of Nuclear Science and Eng., May 2015



(2-3) E. A. Bates, "Optimization of Deep Boreholes for Disposal of High-Level Nuclear Waste," PhD Thesis, MIT Dept. of Nuclear Science and Eng., Feb. 2015

(2-4) "Spent Fuel Decay Heat Measurements Performed at the Swedish Central Interim Storage Facility," NUREG/CR 6971, ORNL/TM-2008/016

(2-5) F. E. Dozier, M. J. Driscoll, J. Buongiorno, "Host Rock Temperature around a Borehole Containing HLW," Trans. Am. Nucl. Soc., Vol. 105, Nov. 2011

## Chapter 3 Threats to Excellent Performance

### 3.1 Chapter Introduction

Looking back at our investigations of features, events and processes associated with the deep borehole concept, three items in particular emerged as potential causes of or contributors to premature and consequential failure of confinement:

- ⊙ high permeability in the plugs which seal the caprock zone
- ⊙ strong vertical natural convection linking the entombment zone through the caprock and overburden layers, to the inhabited biosphere
- ⊙ loss of waste cooling during handling, resulting in overheating-induced waste form degradation.

As summarized in the sections which follow, it was possible to develop strong cases in support of concluding that all of the above threats are avoidable.

### 3.2 Caprock Plug Leakage

Two phenomena give concern over one's ability to seal the borehole penetration through the caprock zone:

- ⊙ the existing of a drilling-disturbed layer surrounding the interface of the borehole with the host rock
- ⊙ the fact that ordinary Portland cement shrinks during setting, which can open vertical cracks having high permeability relative to both solid intact cement and granitic host rock.

It has been our goal throughout to provide seals which have an effective overall permeability which is less than (or at worst equal to) that of the host rock. In this regard it should be kept in mind that in situ permeability and not that measured in surface laboratories is the appropriate benchmark, since several kilometers of lithostatic pressure (at ~25 MPa/km) can squeeze many cracks shut.

Fortunately the oil and gas well drilling community are also motivated to heal the borehole drilling-disturbed layer, which they accomplish by successive injections of sodium silicate and calcium chloride solutions. This reduces permeability by several orders of magnitude (3-1). This remedy should be one major focus of a test program on a demonstration nuclear waste borehole.

After many iterative modifications, the arrangement sketched in Fig. 3.1 was arrived at. Focusing on the plug zone note the major features:

- a) the hole's steel tube liner, employed during drilling and waste canister emplacement, has been removed, to allow direct contact between plugs and the (healed) host caprock wall;

- b) an upper section, which penetrates sedimentary rock overburden (if present, as usually the case) and/or more highly cracked granitic bedrock, is filled with a mixture of granitic sand and bentonite clay. The obviously compatible sand is available on site from the drilling operations, and bentonite clay is a widely used material in waste repository designs. It swells during water uptake, and acts as an absorber for many chemical species. This close to the surface it will be less affected by high temperature and salinity than deeper into the emplacement zone, where sepiolite clay might be a better choice. A repeat infill segment is also used deeper down.
- c) The caprock layer proper contains (at least) two solid plugs of expansive concrete. Adding MgO to Portland cement is sufficient to produce this material, as we have confirmed in a series of lab tests (3-2) building on prior oil/gas drilling technology.

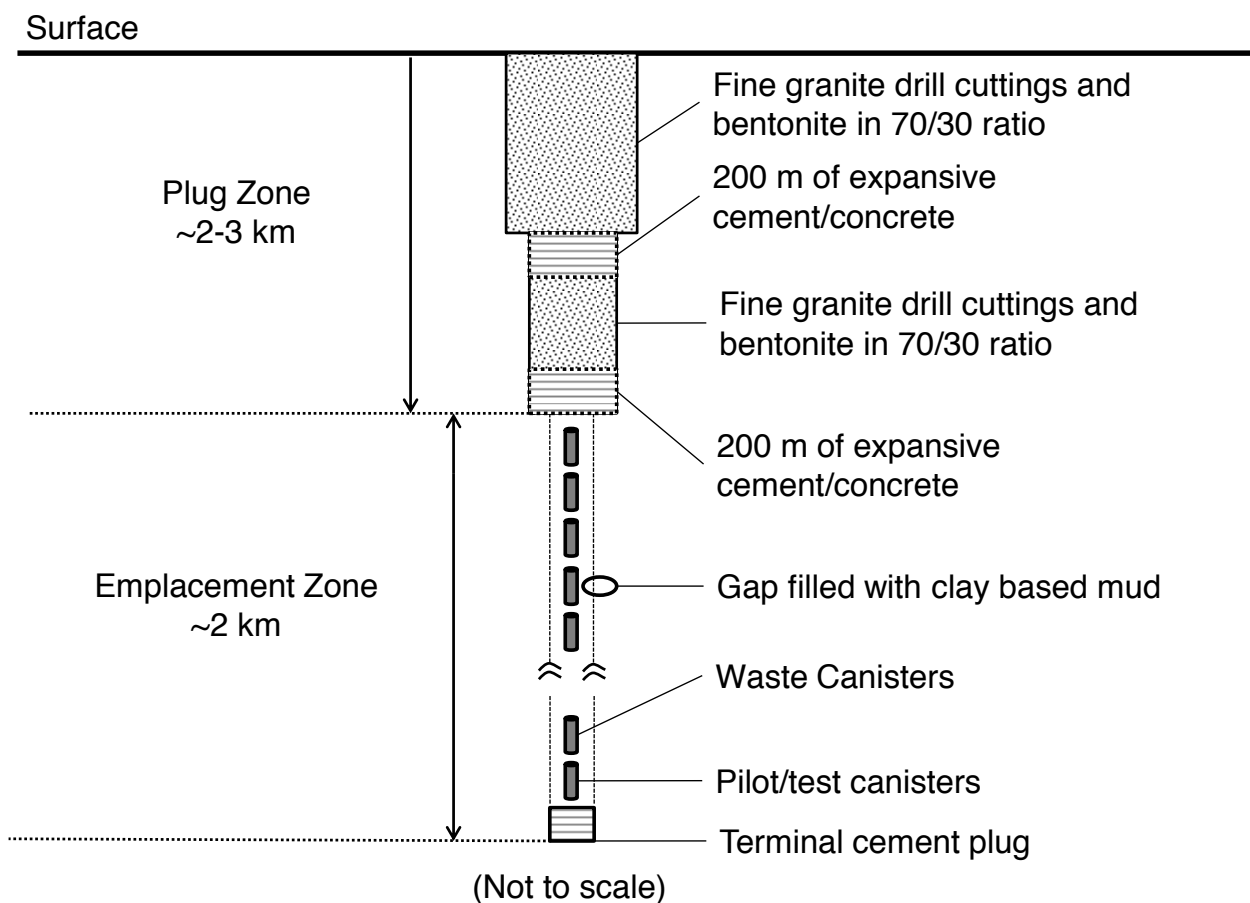


Fig. 3.1. Borehole and Plug Design.

### 3.3 Convective Breakthrough of Water

The most obvious threat leading to waterborne radionuclide release raised by knowledgeable observers is via natural convection of the water contained in interconnected host rock porosity – even though the content is less than one volume percent.

Investigation of this hypothesis is too complicated for a detailed exposition here. Instead we refer the concerned reader to the recently published PhD thesis by Ethan Bates (3-3). What follows merely sketches the basic structure of the technical case for deflation of this concern.

Several hundred years after emplacement, the decay heat is rather uniformly distributed radially within the block of rock surrounding each borehole in the array which makes up a repository field. From then on one can analyze the onset of Rayleigh-Benard like convection between a hotter lower surface (e.g. bottom layer of the caprock zone) and a cooler upper layer (the surface of the earth). In this case several analysts have shown that there is a critical Rayleigh Number, below which convection will not be initiated or sustained. Depending on the detailed boundary conditions employed:

$$(Ra)_c = \frac{g \beta \Delta T H k_m}{\mu \left( \frac{\kappa_{th}}{\rho C p} \right)} > 14 \text{ to } 4\pi^2 \text{ to induce convection}$$

where  $k_m$  = permeability of the porous rock matrix,  $m^2$

$\beta$  = volumetric thermal expansion coefficient of water,  $\sim 7 \times 10^{-4}$  per $^\circ\text{C}$

$\Delta T$  = Temperature difference between hot and cold surfaces (here the bottom and top of the caprock),  $^\circ\text{C}$

$H$  = Thickness of caprock

$\mu$  = viscosity of water, Pa-s

$\kappa_{th}$  = thermal conductivity of caprock, W/ $m^\circ\text{C}$

$\rho C p$  = product of rock density and heat capacity, J/ $m^3 \text{ } ^\circ\text{C}$

Assuming representative values for all parameters involved requires that  $k_m$  be less than about  $10^{-14} m^2$  ( $\sim 0.1$  millidarcy). Granitic bedrock is commonly accessible at lower permeability, hence with a comparable margin against natural convection.

Salinity, dominated by NaCl, increases water density by about  $70 \text{ kg/m}^3$  for every 100 g salt/liter – roughly what one expects at a depth of one or more kilometers in granitic shield bedrock. This is sufficient to offset an increase in water temperature of approximately  $100^\circ\text{C}$ . Thus there is likely to be a natural protection present which would stifle natural convection. One hesitates, however, to require that a prospective site have this feature, let alone postulate a continued presence over tens of thousands of years into the future. Similarly, salt could easily be added to the gap-filler mud in the borehole, but preventing loss by leaching over times measured in eons can not be assured. Thus this feature is probably best treated as a bonus rather than a requirement.

Despite the apparent robustness of this assurance of the absence of convective circulation, the case is not necessarily ironclad. Lubchenko has raised questions with regard to sparse arrays (3-4), and questions still remain on how best to characterize the effective large mesh block permeability of

regions containing extensive crack networks (one aspect being looked into by Mariana Rodríguez Buño in her recently initiated doctoral thesis research).

### 3.4 Loss of Cooling Capability

A simple estimate of the minimum time interval before intervention is needed to prevent overheating can help in planning fuel assembly handling operations. One such metric is the adiabatic heatup rate of coolant-free fuel. This is very conservative because it ignores energy loss by heat transfer to surroundings, and the additional heat storage capability due to material added to the assembly to increase thermal conductivity and crush resistance.

The parameter of interest is the heat capacity. Values for the materials of present concern are as follows:

Constituent	Cp, W hr/kg°C
Zr (i.e. Zircaloy)	0.078
UO <sub>2</sub> , uranium dioxide	0.066

We are interested in assemblies with approximate compositions as follows:

Material	Mass per assembly, kg
	<u>PWR</u>
Zr	150
UO <sub>2</sub>	570

The final input needed is the assembly total power, estimated to be:

PWR	500 W	for 40 years cooling
(One BWR assembly is a factor of ~3 lower.)		

From the preceding, the adiabatic heatup rate is readily estimated:

PWR	10	°C/hr
-----	----	-------

The above rate is tolerable and can be accommodated by procedures which limit uncooled delays to reasonable durations – e.g., less than several hours.

The actual situation is even more favorable – see section 2.2.4 of Chapter 2 on the efficacy of radiation heat transfer.

For this reason we have not delved excessively into handling procedures or technology, since currently available approaches should suffice for our purposes.

### 3.5 Other Recent Technically Based Criticism

In mid-July 2015 a feature article on deep boreholes appeared in Science magazine (3-5). It includes comments solicited from several cognoscenti on their perceived shortcomings of the deep borehole approach. Some points raised, however, elicit obvious counterarguments. Consider that:

- 1) In brief, deeper is much better. For example, rock porosity (hence water content) and permeability decrease with depth. Moreover, ambient chemistry deep in granitic bedrock is reducing ( $E_h \sim -0.3$  volt). This insures low solubility, corrosion and leach rates, plus increased adsorption on host rock surfaces.
- 2) Approximately 50% of continental US land area has granitic bedrock overlain by less than two kilometers of sedimentary overburden. This gives rise to a large number of potential sites.
- 3) Skepticism related to the need for large hole diameters should be tempered by the realization that we are dealing with canisters containing single assemblies, and not the multi-assembly bundles typical of other approaches. Furthermore, one can start with disposal of BWR assemblies, which are roughly equal in number to PWR assemblies, but one-third thinner and a factor of three lower in decay power. This will buy time on the order of decades for evolutionary improvements.

All-in-all, the article is well worth reading and should encourage wider dialog on technological preferences.

### 3.6 Chapter Summary

This chapter has addressed the most prominent features, events and processes which could, hypothetically, lead to failure of a deep borehole repository: inadequate borehole sealing, rampant upward natural convection of water, and self-induced overheating sufficient to damage the entombed waste and/or repository host rock.

The topmost priority in qualification of the deep borehole concept must be for robust and reliable seal deployment. In the end result of our design iterations, diversity and redundancy have been invoked as important guidelines. Thus both solid (expanding cement) and fluid (bentonite plus sand) layers, at least two deep each, have been specified. Attention is also called to the fact that evaluation of thermite plugs is currently underway elsewhere. If successful, strong consideration should be given to adding such plugs as another layer of dispersed defense in depth.

### 3.7 Chapter References

(3-1) R. Sweatman, “Well Cementing Operations,” International Association of Drilling Contractors (IADC), 2015

(3-2) A. Salazar, “The Thermal Conductivity of Filler Materials and Permeability of a Cement Sealant for Deep Borehole Repositories for High Level Nuclear Waste,” SB Thesis, MIT Dept. of Nuclear Science and Engineering, June 2013

(3-3) E. A. Bates, “Optimization of Deep Borehole Repositories for Disposal of High-Level Nuclear Waste,” PhD Thesis, MIT Dept. of Nuclear Science and Engineering, Feb. 2015

(3-4) N. Lubchenko, “Transient Modeling of Host Rock for a Deep Borehole Nuclear Waste Repository,” SM Thesis, MIT Dept. of Nuclear Science and Engineering, June 2015

(3-5) W. Cornwall, “Deep Sleep,” Science, Vol. 349, Issue 6244, 10 July 2015.

## Chapter 4 Performance Metrics

### 4.1 Chapter Introduction

Ultimately, the deep borehole approach must be evaluated both on an absolute basis and relative to other alternatives, using appropriate metrics. The two selected for the present study are cost per kilogram of uranium fuel and dose to the reasonably maximally exposed individual (RMEI). The estimates summarized in this chapter must be regarded as partial and preliminary because of the need for unavailable field data on the cost of siting, drilling and completing fully prototypic boreholes. The lack of a specific site also means significant uncertainty in dose rate to the RMEI in addition to the usual wide spread in stochastic estimates due to the very long time horizon likely to be prescribed – e.g.  $10^4$  to  $10^6$  years based on the now suspended Yucca Mountain licensing proceedings.

### 4.2 Cost of Disposal

Based on the (superseded as of March 2014) DOE waste fee of 1 mill/kWhre, approximately 400 dollars per kilogram of used fuel's pre-burnup uranium has been collected to cover its disposal.

As part of this project Ethan Bates in his PhD thesis (which see) has investigated borehole associated costs and arrived at a best estimated optimized value of 135 \$/kg as shown in Fig. 4.1 from Ref (4-1). Note that this does not include the costs of shipping or waste canister fabrication and loading – which should not differ significantly from those for mined repositories.



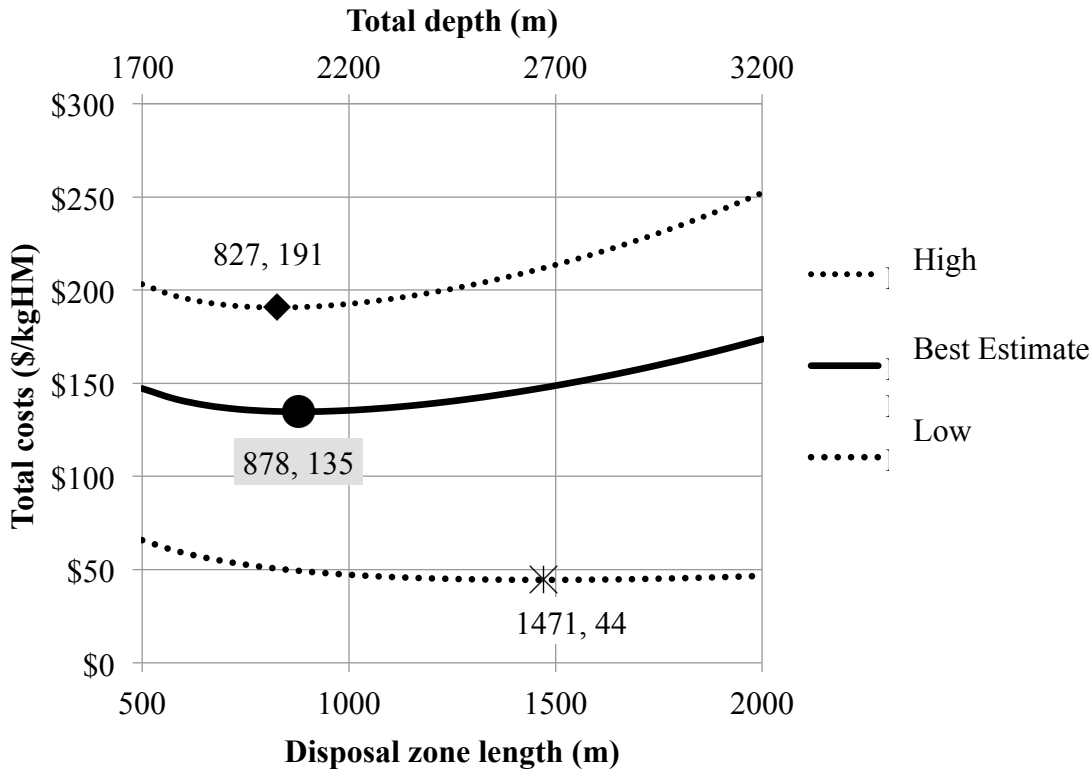


Fig. 4.1. Optimized lower bound, upper bound and best estimate costs for deep boreholes (including drilling, site characterization and waste emplacement (from Ref (4-1))

Two aspects stand out in Fig. 4.1. The first is the wide spread between upper and lower bounds. The second is the relatively flat variation of cost/kg as a function of total depth and disposal zone length. Drilling a demonstration borehole should sharpen these cost projections – but still leave open the extent of reduction for n-th of a kind boreholes. The weak optimum is also encouraging in that it allows changing depth to best suit local host rock conditions – even within the same borehole field. Also noteworthy is that maximum costs are within the waste fee assessment, even without accounting for accumulated interest between collection and expenditure (should that be allowed).

At this point in time a fully credible total cost comparison to shallower mined repository is virtually impossible. Reference (4-2) mentions an expenditure to date on Yucca Mountain of  $\$15 \times 10^9$ , which amounts to 195 \$/kg based on their cited nominal capacity of 77,000 metric tons. However Ref (4-2) also projects a final cost of 100 billion dollars!

Thus, all that can be said at present is that deep boreholes appear competitive, if not cheaper.

#### 4.3 Dose to Future Neighbors

The exposure dose risk from a deep borehole repository promises to be far below regulatory limits. Due to the highly favorable geochemistry downhole, the consensus is that I-129 dominates escapability and the level of radiological threat by an order of magnitude or more for granite host rock. See Table 4.1, originally from Ref (4-4).

Table 4.1 Compilation of Radiological Hazard Rankings for Radionuclides  
in Granite Mined Repositories (4-3)(4-4)

TABLE G-2 Relative Doses to Future Individuals From a Granite Repository Loaded With  
Unreprocessed LWR Spent Fuel

Radionuclide	Half-Life, (years)	Relative Dose Rate <sup>a</sup>			United Kingdom- NRPB <sup>e</sup>
		Sweden- SKI <sup>b</sup>	Sweden- SKB <sup>c</sup>	Finland <sup>d</sup>	
<sup>129</sup> I	$1.57 \times 10^7$	1	1	1	1
<sup>99</sup> Tc	$2.11 \times 10^5$	$1 \times 10^{-5}$		$6 \times 10^{-5}$	$6 \times 10^{-1}$
<sup>135</sup> Cs	$2.3 \times 10^6$	$3 \times 10^{-2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$	$1 \times 10^{-1}$
<sup>14</sup> C	$5.73 \times 10^3$	$3 \times 10^{-5}$		$6 \times 10^{-2}$	$4 \times 10^{-12}$
<sup>36</sup> Cl	$3.01 \times 10^5$			$2 \times 10^{-3}$	$2 \times 10^{-9}$
<sup>79</sup> Se	$6.5 \times 10^4$	$3 \times 10^{-3}$		$1 \times 10^{-2}$	$2 \times 10^{-11}$
<sup>126</sup> Sn	$1.0 \times 10^5$		$1 \times 10^{-2}$	$6 \times 10^{-4}$	$2 \times 10^{-14}$
<sup>226</sup> Ra	$1.6 \times 10^3$		$1 \times 10^{-3}$	$2 \times 10^{-2}$	
<sup>231</sup> Pa	$3.28 \times 10^4$	$2 \times 10^{-2}$	$3 \times 10^{-2}$	$4 \times 10^{-1}$	
<sup>234</sup> U	$2.45 \times 10^5$	$1 \times 10^{-8}$		$6 \times 10^{-5}$	
<sup>238</sup> U	$4.47 \times 10^9$	$1 \times 10^{-8}$		$1 \times 10^{-5}$	
<sup>237</sup> Np	$2.14 \times 10^6$	$3 \times 10^{-5}$		$4 \times 10^{-4}$	
<sup>239</sup> Pu	$2.41 \times 10^4$	$3 \times 10^{-5}$		$2 \times 10^{-3}$	
<sup>240</sup> Pu	$6.56 \times 10^3$	$1 \times 10^{-8}$			
<sup>242</sup> Pu	$3.73 \times 10^5$	$3 \times 10^{-5}$		$4 \times 10^{-2}$	
<sup>243</sup> Am	$7.38 \times 10^3$			$4 \times 10^{-4}$	

<sup>a</sup>Maximum dose rate from the listed radionuclide divided by the maximum dose rate from the radionuclide that contributes the largest dose. The maximum values occur at different times.

<sup>b</sup>SKI - Swedish Nuclear Power Inspectorate (1991).

<sup>c</sup>SKI - Swedish Nuclear Fuel and Waste Management Co. (1992).

<sup>d</sup>Vieno et al. (1991).

<sup>e</sup>Mobbs et al. (1991) United Kingdom - National Radiation Protection Board (UK-NRPB). Calculated doses from technetium and actinides are not included because solubility limits were ignored. Solubility limits are included in all other safety analyses reviewed here.

To the above precedent we can add the more recent assessment published by Sandia (4-5), which also downselects to I-129, as do our own findings (4-3).

In nature, of course, iodine is essentially all I-127, the stable, non-radioactive isotope. Hence dilution of released I-129 is inevitable. This explains, in part, why experts in the field downplay I-129 as a serious radiological threat.

For example:

Moeller (4-6) notes that:

“Iodine-129 – The specific activity of I-129 is so low that even if the thyroid were saturated, the dose would be inconsequential. In fact, the National Council on Radiation Protection & Measurements has concluded that I-129 does not pose a meaningful threat of thyroid cancer in humans.”

and Eisenbud (4-7) adds:

“Iodine-129 is one of the longest-lived nuclides produced in fission, with a half-life of  $1.57 \times 10^7$  years. It is estimated that by the year 2000, about 2500 Ci of  $^{129}\text{I}$  will have been produced by power reactors. Iodine is such a soluble element and the half-life of  $^{129}\text{I}$  is so long that the  $^{129}\text{I}$  will eventually enter the stable iodine pool. The total amount of iodine that can be absorbed into the thyroid is under metabolic control and is limited to about 0.012 g. Iodine-129 cannot deliver a significant dose to the thyroid because this would require deposition of 34 g of  $^{129}\text{I}$ , several thousand times the average normal value (NCRP, 1983).”

\* \* \*

Nevertheless, I-129, as the most escape-prone radionuclide, is a useful bellwether for evaluating confinement effectiveness, and we will continue to employ it in that role, rather than as a genuine hazard.

In other words, lacking a specific site at present prevents us from laying out a well-defined scenario for transport, escape, and ingestion of I-129. But the expectation is that, no matter what, the end result will be tolerable.

#### 4.4 Chapter Findings

The performance metrics selected: cost per kilogram of uranium in as-loaded fuel, and dose rate to the reasonably maximally exposed individual (RMEI), are both sufficiently promising to support moving ahead with a more aggressive program to demonstrate and deploy deep boreholes in place of, or in addition to, shallower mined repositories for used nuclear fuel assemblies and/or their reprocessed constituents.

#### 4.5 References for Chapter 4

- (4-1) E. A. Bates, “Optimization of Deep Boreholes for Disposal of High-Level Nuclear Waste,” PhD Thesis, MIT Dept. of Nuclear Science and Engineering, Feb. 2015
- (4-2) Nuclear Waste News, Vol. 35, No. 6, April 17, 2015
- (4-3) M. J. Driscoll et al., “Radionuclide Transport and Escape to Biosphere from Deep Boreholes,” March 20, 2014, MIT Dept. of Nuclear Science and Eng., Topical Report
- (4-4) National Research Council, “Nuclear Wastes Technologies for Separations and Transmutation,” National Academy Press (1996), p. 330
- (4-5) P. V. Brady et al., “Deep Borehole Disposal of High-Level Radioactive Waste,” SAND2009-4401, Aug. 2009
- (4-6) D. Moeller, Letter to *Nuclear News*, April 2011, Vol. 54, No. 4, p. 24
- (4-7) M. Eisenbud, *Environmental Radioactivity*, 3<sup>rd</sup> Ed., Academic Press, 1987

## Chapter 5 Summary, Conclusions and Recommendations

### 5.1 Synopsis

This report summarizes the progress made over the past three years covered by Award No. NEUP FY 2012 R&D #3298, which in turn built upon MIT work going back some twenty-five years, the last six of which involved collaboration with a team of Sandia experts.

Table 5.1 (a repeat of Table 1.1) summarizes the end-state features of our recommended deep borehole version going forward. The entries are largely self-explanatory. They describe a simple “plain vanilla” design which can be constructed today using readily available commercial technology as deployed by the oil and gas well drilling industry. An even broader and deeper synthesis is documented by Bates (5-1) who was supported as a research assistant on this contract for the latter stages of his work. Accessing this document is highly recommended for those having a more than casual interest in deep boreholes for nuclear waste disposal.

Table 5.1  
Recommended Configuration of Deep Borehole HLW Repositories (as of 9/1/15)

Aspect	Choices*	Motivation
Host medium	granitic bedrock (salt: dome or bedded) [shale or basalt]	dry, with low permeability; ubiquitous availability
Terrain	no sedimentary overburden ( $\leq$ 1km overburden) [shale or salt caprock]	avoidance of increased cost and potential presence of useful aquifers; discourages local habitation
Hole specifications	20 inches: 50 cm ID ~ 1 km of caprock unlined, 1 to 2 km waste zone, lined vertical holes in emplacement zone perforated/slotted liner (slanted holes) [multibranch holes]	<ul style="list-style-type: none"> <li>• to accommodate canisters encapsulating intact PWR fuel assemblies; can reduce for BWR or reprocessing waste forms</li> <li>• to avoid crushing by canister stack</li> <li>• to equalize radial pressure, allow water ingress/egress, gas venting</li> </ul>
Repository field	200 m pitch ~ 400 holes in 20 x 20 array (100m or 300m pitch)	<ul style="list-style-type: none"> <li>• to minimize far future radial temperature peaking</li> <li>• to hold ~80,000 MT (US legacy used fuel)</li> <li>• to realize economies of scale and facilitate collective licensing</li> </ul>
Canister features	made of drillpipe segment (or cast iron cylinder) internal voids filled with granitic sand, (drill cuttings) [or zinc casting alloy] (caster ring on ends)	<ul style="list-style-type: none"> <li>• strong, corrosion resistant under downhole geochemistry</li> <li>• to counter crushing</li> <li>• Zn will exclude water</li> </ul>
Canister/liner gap	fill with graphite/sepiolite mud (other muds), [dry] [concrete with SiC gravel to help thwart retrieval]	high thermal conductivity provides lubrication; blocks vertical convection; facilitates retrieval if this is required. Helps offset stress on hole wall
Caprock plugs	Sequences of: <ul style="list-style-type: none"> <li>• expanding cement</li> <li>• bentonite + granitic sand</li> <li>• [thermite]</li> </ul>	to provide diverse and redundant low permeability seals

\*Near term preferences listed first, alternatives in parentheses ( ); potential future developments in brackets [ ].

## 5.2 Recommendations

One major conclusion is that siting and drilling a demonstration borehole specifically dedicated to validation of used LWR fuel disposal should be undertaken. Table 5.2 summarizes this proposition as submitted by our borehole group via Prof. M. J. Demkowicz of the MIT Materials Science and Engineering Department to a DOE meeting on basic research needs.

Table 5.2

### INPUT TO DOE MEETING ON BASIC RESEARCH NEEDS IN JULY 2015

#### Deep Boreholes for Used Nuclear Fuel and HLW Disposal

The most compelling need is for prompt creation of a demonstration borehole and its use for key confirmatory experiments:

- ⊙ use of state-of-the-art airborne and on-surface methods to screen for qualified sites
- ⊙ drill a demonstration (but not necessarily full scale) borehole of several inches diameter and several kilometers deep, using existing technology, including all key prototypic features such as insertion of a liner
- ⊙ measurement of downhole chemistry and thermal/mechanical/hydraulic characteristics, with special attention to saline water and granitic host rock, and their evolution over time
- ⊙ emplacement of an electrically heated simulated waste canister to confirm decay heat accommodation

To realize these goals the existing program led by our collaborators at the Sandia National Laboratories should be supported.

\* \* \*

In parallel, improved technologies for drilling the 20 inch (~50 cm) boreholes, needed for commercial deployment, should be more aggressively pursued.

## 5.3 Looking Ahead

In the future a high priority should be given to development of circumferential canister end wheels and their use to enable slant-path boreholes. Figure 5.1 shows a crude model of one potential configuration.

An initial scoping study on these advances has been completed by a visiting student (5-2). His work identified many advantages, among which are:

- ⊙ reduction of tolerances on hole linearity and radius of curvature for both vertical and slant-path boreholes;
- ⊙ easier withdrawal, hence retrievability, should this be needed;
- ⊙ near-horizontal emplacement zones which reduces stack and hydrostatic pressures on the bottom-most waste canisters.

Design and manufacture of rugged, reliable canister end fittings housing wheels should be relatively straightforward given the long term and widespread experience with the rather similar roller-cone drill bits in the oil and gas well drilling industry.



Fig. 5.1. Model Showing Canister End 6-Wheel Roller Ring.



Also worth continued evaluation is the use of zinc-aluminum alloy in place of sand as an in-canister void filler. This would allow disposal of wastes having a much higher decay linear power density than PWR legacy fuel. Progress to date is summarized in Appendix C, and follow-on work will be conducted under other auspices, culminating in a report by Yongsoo Park, scheduled for completion in January 2016.

#### 5.4 References for Chapter 5

(5-1) Ethan A. Bates, “Optimization of Deep Borehole Repositories for Disposal of High-Level Nuclear Waste,” PhD Thesis, MIT Dept. of Nuclear Science and Engineering, Feb. 2015

(5-2) Roberto Formento Cavaier, “Wheeled Canisters and Slant-Path Boreholes for Disposal of Nuclear Spent Fuel,” Masters Degree in Nuclear and Energy Engineering, Politecnico di Torino, July 2015

## Appendix A

### OPTIMIZATION OF DEEP BOREHOLES FOR DISPOSAL OF HIGH-LEVEL NUCLEAR WASTE

By Ethan Allen Bates

Submitted to the Department of Nuclear Science and Engineering on December 1<sup>st</sup>, 2014 in partial fulfillment of the requirements for the degree of Doctor of Philosophy in  
Nuclear Science and Engineering

#### Abstract

This work advances the concept of deep borehole disposal (DBD), where spent nuclear fuel (SNF) is isolated at depths of several km in basement rock. Improvements to the engineered components of the DBD concept (e.g., plug, canister, and fill materials) are presented. Reference site parameters and models for radionuclide transport, dose, and cost are developed and coupled to optimize DBD design. A conservative and analytical representation of thermal expansion flow gives vertical velocities of fluids vs. time (and the results are compared against numerical models). When fluid breakthrough occurs rapidly, the chemical transport model is necessary to calculate radionuclide concentrations along the flow path to the surface. The model derived here incorporates conservative assumptions, including instantaneous dissolution of the SNF, high solubility, low sorption, no aquifer or isotopic dilution, and a host rock matrix that is saturated (at a steady state profile) for each radionuclide. For radionuclides that do not decay rapidly, sorb, or reach solubility limitations (e.g., I-129), molecular diffusion in the host rock (transverse to the flow path) is the primary loss mechanism.

The first design basis failure mode (DB1) assumes the primary flow path is a 1.2 m diameter region with 100× higher permeability than the surrounding rock, while DB2 assumes a 0.1 mm diameter fracture. For the limiting design basis (DB1), borehole repository design is constrained (via dose limits) by the areal loading of SNF (MTHM/km<sup>2</sup>), which increases linearly with disposal depth.

In the final portion of the thesis, total costs (including drilling, site characterization, and emplacement) are minimized (\$/kgHM) while borehole depth, disposal zone length, and borehole spacing are varied subject to the performance (maximum dose) constraint. Accounting for a large uncertainty in costs, the optimal design generally lies at the minimum specified disposal depth (assumed to be 1200 m), with disposal zone length of 800-1500 m and borehole spacing of 250-360 meters. Optimized costs range between \$45 to \$191/kgHM, largely depending on the assumed emplacement method and drilling cost. The best estimate (currently achievable), minimum cost is \$134/kgHM, which corresponds to a disposal zone length of ~900 meters and borehole spacing of 272 meters.

**Thesis Supervisor:** Michael J. Driscoll

**Title:** Professor Emeritus of Nuclear Science and Engineering

**Thesis Supervisor:** Emilio Baglietto

**Title:** Assistant Professor of Nuclear Science and Engineering

**Thesis Reader:** Jacopo Buongiorno

**Title:** Associate Professor of Nuclear Science and Engineering

## APPENDIX B

## BIBLIOGRAPHY OF PUBLICATIONS, 1990 THROUGH 2015

## MIT DEEP BOREHOLE PROJECTS

- (B-1) W.-S. Kuo, "Evaluation of Deep Drillholes for High Level Nuclear Waste Disposal," Nucl. Eng./SM Thesis, MIT Nuclear Engineering Dept., 1991
- (B-2) W.-S. Kuo, M.J. Driscoll, J.W. Tester, "Re-evaluation of the Deep Drillhole Concept for Disposing of High-Level Nuclear Wastes," Nuclear Science Journal, Vol. 32, No. 3, June 1995
- (B-3) C.I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2004
- (B-4) V.K. Anderson, "An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2004
- (B-5) C.G. Sizer, "Minor Actinide Waste Disposal in Deep Geological Boreholes," SB Thesis, MIT Dept. of Nuclear Science and Engineering, May, 2006
- (B-6) C.I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste, SM Thesis, MIT Dept. of Nuclear Science and Engineering, May 2006
- (B-7) S. Shaikh, "Effective Thermal Conductivity Measurements Relevant to Deep Borehole Nuclear Waste Disposal," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Jan. 2007
- (B-8) C.G. Sizer, C.J. Hoag, S. Shaikh, M.J. Driscoll, "Partitioning and Interment of Selected High Level Wastes," Trans. Am. Nucl. Soc., Vol. 96, June 2007
- (B-9) K.G. Jensen, M.J. Driscoll, "Siting of a Deep Borehole Repository for High Level Nuclear Waste in the United States," Research Report, MIT Dept. of Nuclear Science and Eng., 2008
- (B-10) T.A. Moulton, "Parametric Study of the Total System Life Cycle Cost of an Alternate Nuclear Waste Management Strategy Using Deep Boreholes," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2008
- (B-11) B. Sapiie and M.J. Driscoll, "A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes," Center for Advanced Nuclear Energy Systems, MIT-NFC-TR-109, 2009.
- (B-12) B. Sapiie, M.J. Driscoll, K.G. Jensen, "Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes," MIT-NFC-TR-113, Jan. 2010
- (B-13) K.G. Jensen, M.J. Driscoll, "A Framework for Performance Assessment and Licensing of Deep Borehole Repositories," MIT-NFC-PR-115, March 2010

- (B-14) K.G. Jensen, M.J. Driscoll, "HLW Deep Borehole Design and Assessment: Notes on Technical Performance," MIT-NFC-PR-116, April 2010
- (B-15) J.S. Gibbs, "Feasibility of Lateral Emplacement in Very Deep Borehole Disposal of High Level Nuclear Waste," Naval Engineer and Nuclear Engineer Thesis, MIT, June 2010
- (B-16) K.G. Jensen, M.J. Driscoll, "Plugging of Deep Boreholes for HLW Disposal," MIT-NFC-PR-121, July 2010
- (B-17) M.J. Driscoll, K.G. Jensen, "Deep Borehole Attributes and Performance Requirements," MIT-NFC-PR-120, Sept. 2010
- (B-18) P.V. Brady, M.J. Driscoll, "Deep Borehole Disposal of Nuclear Waste: A Report from a Sandia-MIT Workshop held March 15, 2010 in Washington, DC," Radwaste Solutions, Vol. 17, no. 5, Sept./Oct. 2010
- (B-19) J.S. Gibbs, J. Buongiorno, M.J. Driscoll, "A Multibranch Borehole Approach to HLW Disposal," Proc. of IHLRWMC, April 2011
- (B-20) K.G. Jensen, M.J. Driscoll, "Policy Issues Associated with Deep Borehole HLW Disposal," Proc. of IHLRWMC, April 2011
- (B-21) E.A. Bates, M.J. Driscoll, J. Buongiorno, "Drop-in Concept for Deep Borehole Canister Emplacement," Paper no. 3304, Proc. of IHLRWMC 2011, Albuquerque, NM, April 10-14, 2011
- (B-22) E. Bates, "A Drop-in Concept for Deep Borehole Canister Emplacement," SB and SM in Nuclear Science and Engineering, MIT, May 2011
- (B-23) D. Cabeche, "Water Borne Transport of High Level Waste in Very Deep Borehole Disposal of High Level Nuclear Waste," SB Thesis, MIT Dept. of Nuclear Science and Eng., June 2011
- (B-24) F. Dozier, "Feasibility of Very Deep Disposal of U.S. Defense Nuclear Wastes," Master of Science Thesis, MIT Dept. of Nuclear Science and Engineering, June 2011
- (B-25) F.E. Dozier, M.J. Driscoll, J. Buongiorno, "Host Rock Temperature around a Borehole Containing HLW," Trans. Am. Nucl. Soc., Vol. 105, Washington DC, Nov. 2011, pp. 229-231
- (B-26) E.A. Bates, J. Buongiorno, E. Baglietto, M.J. Driscoll, "Transient Thermal Modeling of a Deep Borehole Repository," Trans. Am. Nucl. Soc., Vol. 106, June 2012
- (B-27) M.J. Driscoll, K.G. Jensen, "Policy Issues Associated with Deep-Borehole HLW Disposal," Radwaste Solutions, Vol. 19 no. 3, July-Aug., 2012

- (B-28) M.J. Driscoll, R.K. Lester, K.G. Jensen, B.W. Arnold, P.N. Swift, P.V. Brady, "Technology and Policy Aspects of Deep Borehole Nuclear Waste Disposal," Nuclear Technology, Vol. 180 no.1, Oct. 2012
- (B-29) A. Salazar, E.A. Bates, M.J. Driscoll, "Plugging of Deep Boreholes Used for HLW Disposal," Trans. Am. Nucl. Soc., Vol. 107, Nov. 2012, p. 293
- (B-30) E.A. Bates, E. Baglietto, M.J. Driscoll, J. Buongiorno, "Onset and Stability of Natural Convection in Deep Boreholes," IHLRWM Conference Proceedings, Albuquerque, April 2013
- (B-31) A. Salazar, "Effect of Temperature on Permeability of Cement Sealant for Deep Borehole Repositories," Proc. of ANS Student Conference, Boston, April 2013
- (B-32) E.A. Bates, "Onset and Stability of Natural Convection in Deep Boreholes," Proc. of ANS Student Conference, Boston, April 2013
- (B-33) E.A. Bates, C. Forsberg, "Radiological Implications of Extended Storage of Spent Nuclear Fuel," Proc. of IHLRWMC, 2013
- (B-34) A. Salazar, "The Thermal Conductivity of Filler Materials and Permeability of a Cement Sealant for Deep Borehole Repositories for High Level Nuclear waste," SB Thesis, MIT Dept. of Nuclear Science and Engineering, May 2013
- (B-35) E. Wium, Report: "Canister Crushing Resistance for Deep Borehole Disposal of Nuclear Waste," MIT, Undergraduate Research Opportunities Program (UROP), Aug. 2013
- (B-36) W. De Maio, E. Bates, "Salinity and Density in Deep Boreholes," MURJ, Vol. 26, Fall 2013.
- (B-37) N. Lubchenko, E. Baglietto, "BeaVeR – A Numerical Thermal-Hydrologic Code Modeling the Host Rock around a HLW Borehole," Topical Report, MIT Dept. of Nuclear Science and Engineering, Oct. 20, 2013
- (B-38) N. Lubchenko, E. Baglietto, M.J. Driscoll, "Towards the Development and Application of Borehole Virtual Reality Simulation Tools," Trans. Am. Nucl. Soc., Vol. 109, Nov. 2013, p. 367
- (B-39) M.J. Driscoll, J. Buongiorno, E. Baglietto, E.A. Bates, N. Lubchenko, "Radionuclide Transport and Escape to Biosphere from Deep Boreholes," Topical Report, MIT Dept. of Nuclear Science and Engineering, March 31, 2014
- (B-40) E. Baglietto, E.A. Bates, N. Lubchenko, M.J. Driscoll, J. Buongiorno, "Thermal / Hydraulic / Mechanical Effects in Canister-to-Rock Gaps of Deep Boreholes for HLW Disposal," Topical Report, MIT Dept. of Nuclear Science and Engineering, March 31, 2014
- (B-41) E.A. Bates, M.J. Driscoll, R.K. Lester, B.W. Arnold, "Can Deep Boreholes Solve America's Nuclear Waste Problem," Energy Policy, Vol. 72, Sept. 2014

- (B-42) E.A. Bates, J. Buongiorno, E. Baglietto, M.J. Driscoll, “Mechanical Stresses Affecting Deep Borehole Disposal of High Level Nuclear Waste,” Proc. of ICONE-22, July, 2014
- (B-43) A. Salazar, “Permeability Analysis of Cement Sealant for Deep Borehole Repositories,” Trans. Am. Nucl. Soc., Vol. 111, Nov. 2014
- (B-44) E.A. Bates, A. Salazar, M.J. Driscoll, E. Baglietto and J. Buongiorno, “Plug Design for Deep Borehole Disposal of High-Level Nuclear Waste,” Nucl. Technol., Vol. 188, No. 3, Dec. 2014
- (B-45) E.A. Bates, “Optimization of Deep Borehole Repositories for Disposal of High-Level Nuclear Waste,” Ph.D. Thesis, MIT Dept. of Nuclear Science and Engineering, Feb. 1, 2015
- (B-46) A. Andriatis, M.J. Driscoll, “Evaluation of Graphite Mud for Use as a Gap-Fill Material in HLW Deep Borehole Repositories,” Topical Report, MIT Dept. of Nuclear Science and Engineering, Feb. 2015
- (B-47) N. Lubchenko, “Transient Modeling of Host Rock for a Deep Borehole Nuclear Waste Repository,” SM Thesis, MIT Dept. of Nuclear Science and Engineering, June 2015
- (B-48) N. Lubchenko (MIT) et al., “Modeling of the Groundwater Transport around a Deep Borehole Nuclear Waste Repository,” NURETH-16, Aug. 30, 2015

To order MIT theses go to MIT Libraries website at <http://libraries.mit.edu>, search for document desired under the search drop-down “Books and more at MIT”; when the item shows up, make choice and under “Shelf access” click on “request item”; under “Availability/Holdings Display” click “copy options” and make selection from the menu that opens up.

## Appendix C

### Draft Transaction Submitted to ANS for Fall 2015 Meeting

#### Thermal resistance reduction in cast metal filled used nuclear fuel canisters

Yongsoo Park, Thomas J. McKrell, and Michael J. Driscoll

*Massachusetts Institute of Technology: 77 Massachusetts Ave, Cambridge, MA 02139;  
yspark@mit.edu, tmckrell@mit.edu, mickeyd@mit.edu*

#### INTRODUCTION

The necessity of filling the void spaces in used nuclear fuel (UNF) canisters has been considered during the past several decades to immobilize the assembly and structurally support the canister during transportation and storage. Various types of materials were proposed as summarized in ref [1] and these include the concept of metal casting, which can be superior compared to others in terms of radionuclides encapsulation by providing another solid barrier, and decay heat removal due to the high thermal conductivity of metals. The latter becomes most important for UNF from fast reactors, which are expected to have much higher decay heat production compared to conventional thermal reactors. However, it is well known that a gap is formed between the cast and the mold due to solidification shrinkage and this significantly increases the thermal resistance during and after cooling the melt [2].

A method to prevent this gap formation is to foster a metallic bonding between the canister and the molten metal. To achieve this; the surface oxide of the canister should be removed. For example, in the hot-dip galvanizing process, a fluxing agent ( $\text{ZnCl}_2/\text{NH}_4\text{Cl}$ ) is used to remove any oxides to allow adhesion between the coating and the steel substrate. However, direct usage of such an agent in a UNF casting process should be avoided since it is highly corrosive unless the residues are completely removed and it decomposes when it is exposed to high temperature, i.e., above 423K. Note that the canister should be heated up to prevent early solidification of the molten fill which should be above the decomposition temperature of the agent. One possible approach is, however, using a pre-galvanized product, where its outermost layer of the coating is pure zinc, with zinc or zinc based alloys as a cast metal. Heating up the canister and the cast metal above the melting point of pure zinc will melt the layer, detaching the zinc oxide from the surface, if there are any, and allowing a direct contact between the remaining coating (Fe-Zn phases) and liquid zinc or liquid zinc based alloy.

This study first examines the thermal resistance of a steel mold filled with a high thermal conductivity metal. Secondly, the feasibility of the approach; using a pre-galvanized steel with a zinc based alloy to interfere with gap formation, is tested. Zn-4Al, having the nearest eutectic composition among commercially sold zinc aluminum alloys, was used as a cast metal in both experiments.

#### DESCRIPTION OF THE ACTUAL WORK

Two experiments were performed in this work. Firstly, effective thermal conductivity of cast Zn-4Al with a gap was measured to examine how the presence of the gap reduces its value. Low carbon steel was used as the mold. It was degreased but not pickled before the experiment and the furnace was not filled with inert gas. The lack of a cover gas allows for oxidation to occur assisting with the prevention of adhesion between the cast and the mold. After melting, a holder with thermocouples and a rod heater at the center was assembled before the melt started to solidify. Thermocouples were fixed near the mold wall and next to the surface of the heater to measure the thermal conductivity of the cast. The mold was directionally solidified from the bottom with water while the wall was insulated to minimize casting defects. Plane front solidification was confirmed with measured temperatures during solidification. After cooling the cast metal to room temperature, another thermocouple was attached on the outer wall of the mold and effective thermal conductivity was measured. The bottom was insulated to prevent heat loss while the top was not due to the presence of wires. However, the heat loss through the top is negligible due to the void space between the cast and the holder. The thermocouples at the mid-height were used for the measurement. Fig. 1. shows a schematic of the set up.

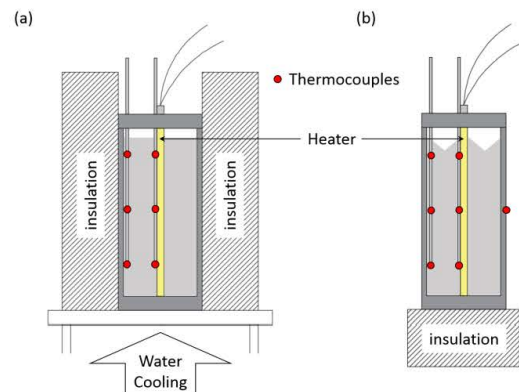


Fig. 1. Schematic of the set up in the first experiment; (a) for cooling and (b) for thermal conductivity measurement.

In the second experiment, the same alloy was placed into a galvanized steel mold and kept inside a furnace. The furnace was steadily heated up to 703K (about 10K higher than the nominal melting temperature of pure zinc) and was maintained at the same temperature for 2 hours. Afterwards, the mold wall was cooled steadily while the bottom was insulated to ease the gap formation. The mold was cut after solidification for inspection. Thermal conductivity measurements for this galvanized steel mold are in progress.

## RESULTS

The effective thermal conductivity from the heater surface to the inner oxidized wall of the mold was calculated from the measured temperatures, known dimensions of the mold and the heater, the power of the heater, and the nominal thermal conductivity of low carbon steels ( $54 \text{ Wm}^{-1}\text{K}^{-1}$ ). The thermal conductivity of the cast Zn-4Al was also calculated with the temperature measurements from the thermocouples that were attached to the holder. The results are shown in Fig. 2. From the figure, the thermal conductivity of Zn-4Al closely matched the nominal value ( $113 \text{ Wm}^{-1}\text{K}^{-1}$ ) while the effective thermal conductivity was much lower. The result shows that the reduction of the effective thermal conductivity was due to the presence of the gap that was formed after solidification. The reduced value, however, is still much higher than other fill candidates such as dry sand [3].

Fig. 3. shows SEM images of the cut piece from the second experiment. Complete adhesion throughout the interface was not observed but a significant portion was successfully adhered without any gaps. Also, from Fig. 3. (c), the gap was formed not because the cast metal failed to adhere to the mold but because of a crack that was initiated during solidification shrinkage. Note that the crack is formed not between the coating and the mold but in the cast metal near to the interface. This is also visible from Fig. 3. (a), which shows an overall view of the crack.

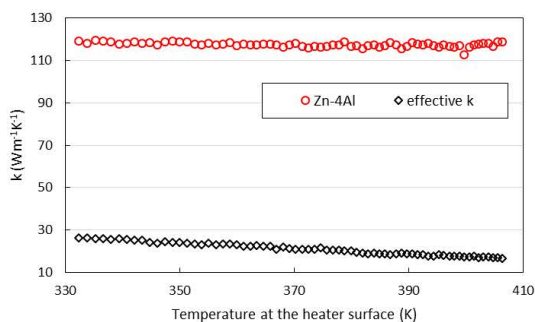


Fig. 2. Measured thermal conductivities of cast Zn-4Al and effective thermal conductivities including the gap as a

function of temperature. This is the first experiment data where the steel/mold wall was oxidized.

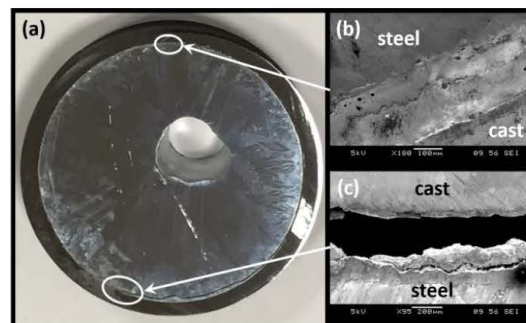


Fig. 3. (a) Image of the cut piece containing solidified Zn-4Al inside a galvanized steel mold, (b) SEM image of a part with complete adhesion, and (c) SEM image of a part with a gap.

From the experiments, it is clear that the effective thermal conductivity is significantly reduced due to the formation of a gap, and the idea of using a pre-galvanized steel to suppress its formation was found to be feasible. Further studies to allow a complete adhesion and how to adopt this technique in a full scale fuel assembly remain.

## ACKNOWLEDGEMENT

This work was supported by the DOE NEUP program.

## REFERENCES

1. S.J. Maheras, et al., "A Preliminary Evaluation of Using Fill Materials to Stabilize Used Nuclear Fuel During Storage and Transportation." PNNL-21664, Pacific Northwest National Laboratory (2012).
2. Y. Nishida, W. Droste, and S. Engler, "The air-gap formation process at the casting-mold interface and the heat transfer mechanism through the gap." *Metallurgical Transactions B* **17**, no. 4, 833-844 (1986).
3. S. Shaikh, "Effective thermal conductivity measurements relevant to deep borehole nuclear waste disposal." SM Thesis, Massachusetts Institute of Technology (2007).